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(54) **METHOD AND APPARATUS FOR ADJUSTING THE PERFORMANCE OF A SYNCHRONOUS MEMORY SYSTEM**

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See application file for complete search history.

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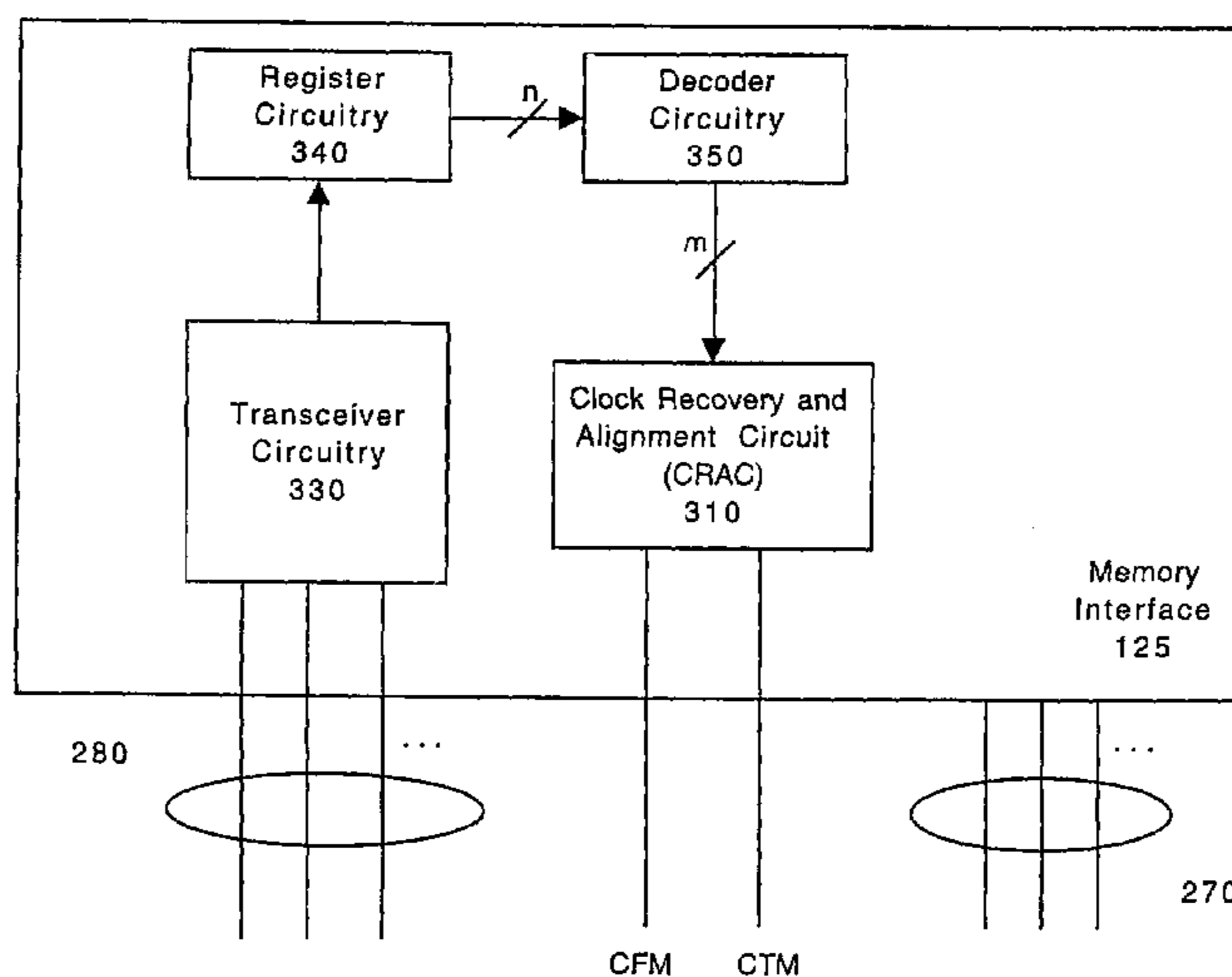
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(57) **ABSTRACT**

A method and apparatus for adjusting the performance of a memory system is provided. A memory control device comprises a master device including a frequency detector, a memory channel, and a memory device coupled to the master device via the memory channel. The memory device includes a decoder designed to receive a control signal from the master device. A clock recovery and alignment circuit receives the control signal from the decoder and adjusts the operating frequency of the memory device in response to the control signal.

**28 Claims, 5 Drawing Sheets**



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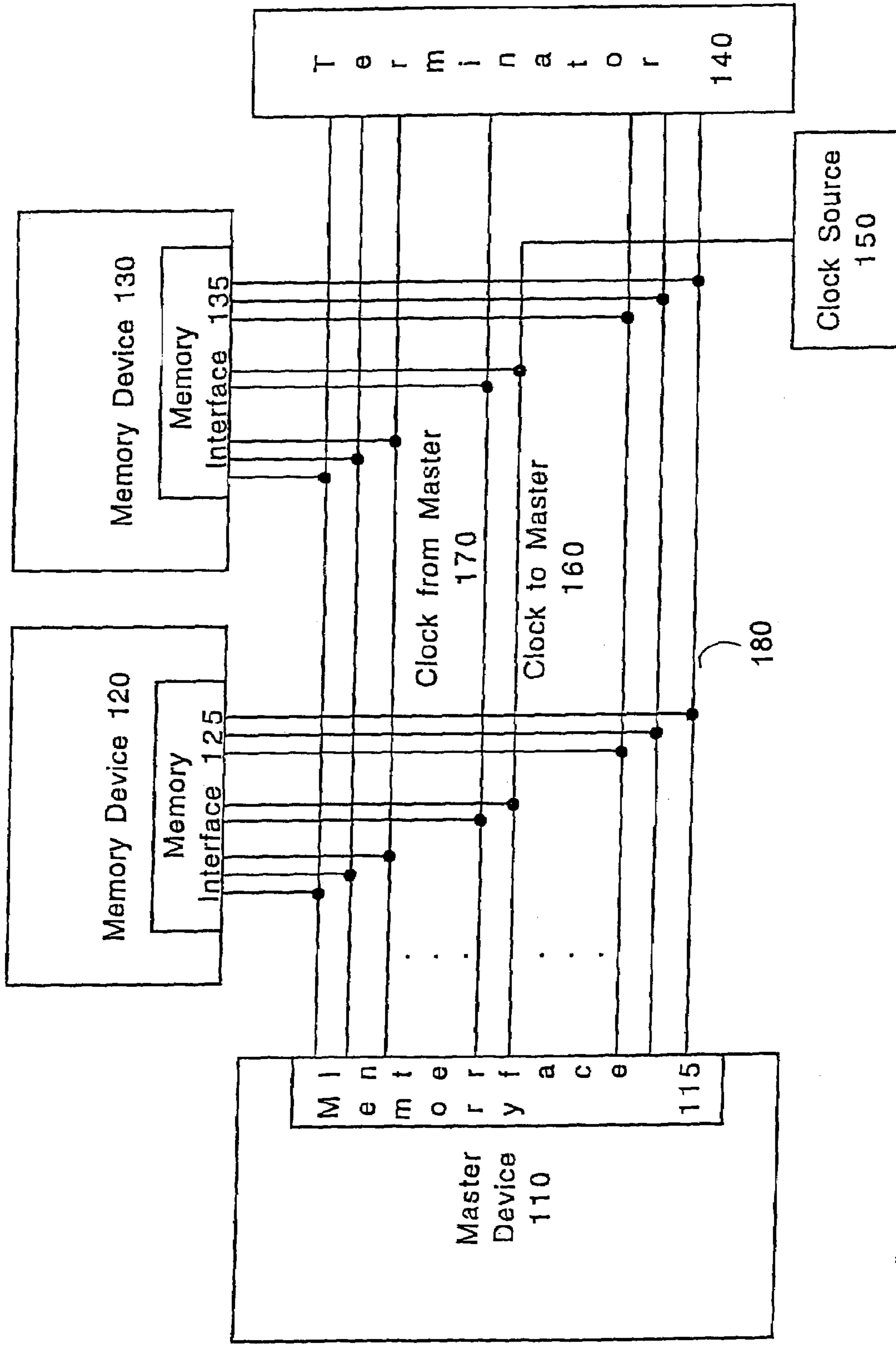


Fig. 1

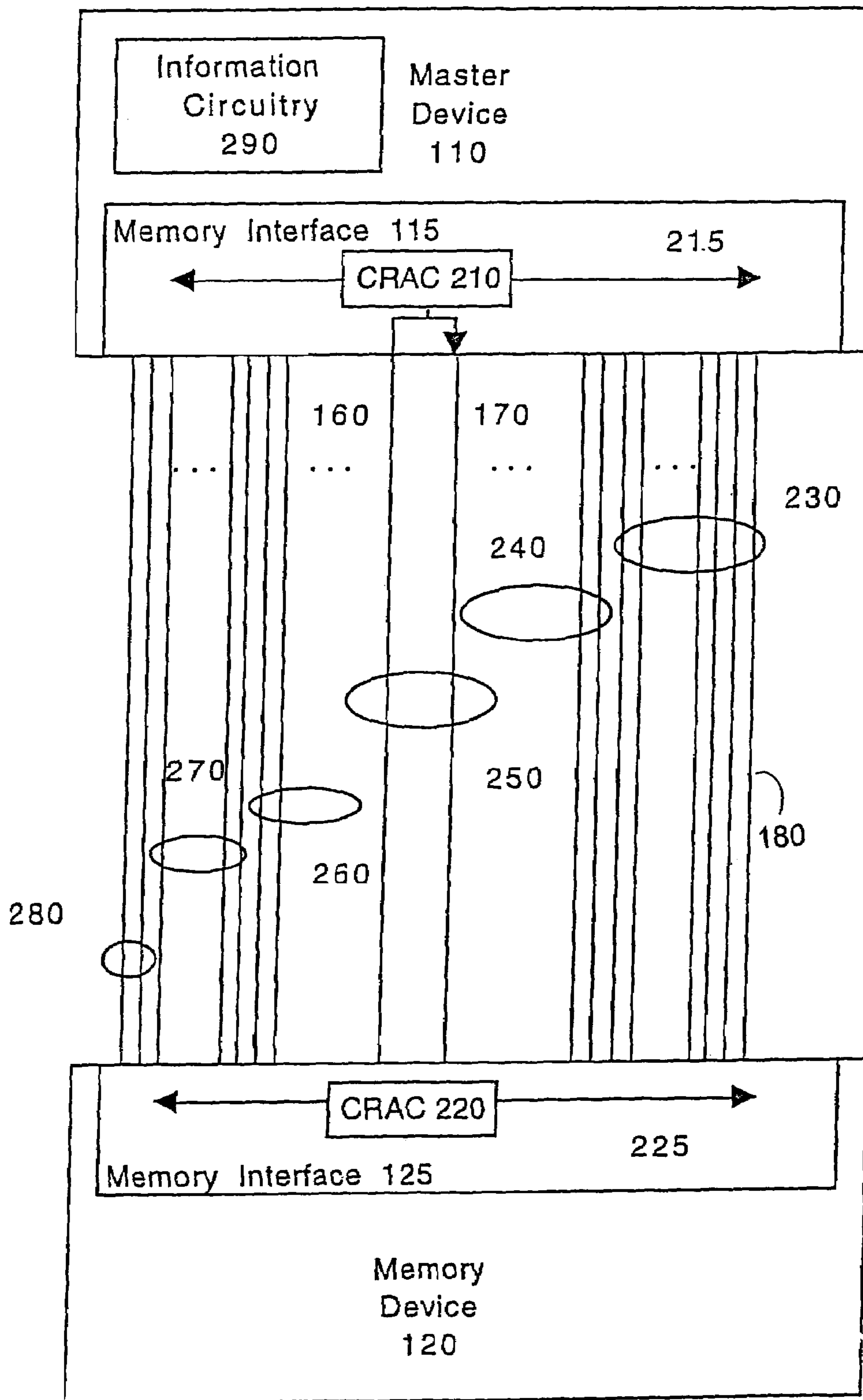


Fig. 2

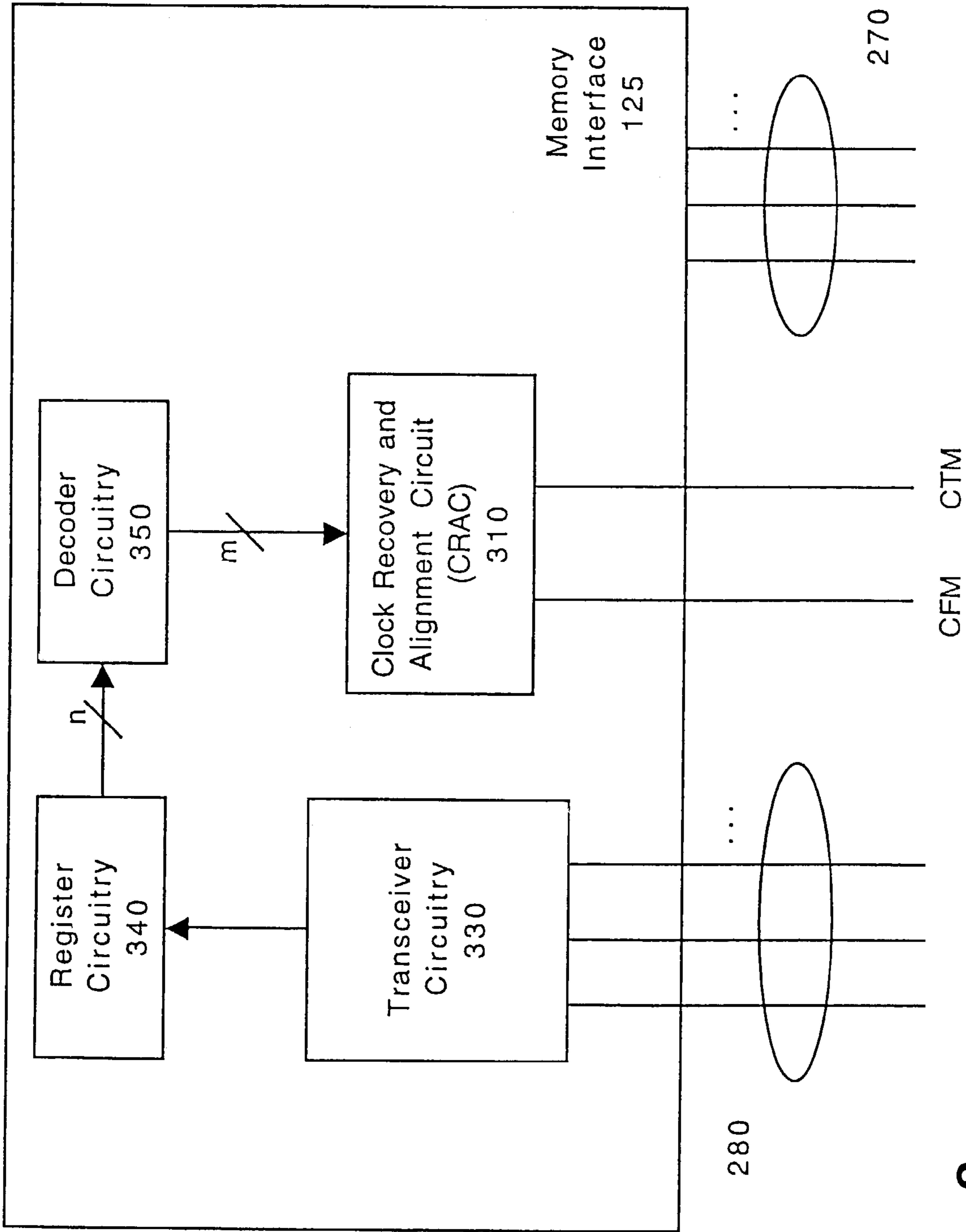


Fig. 3



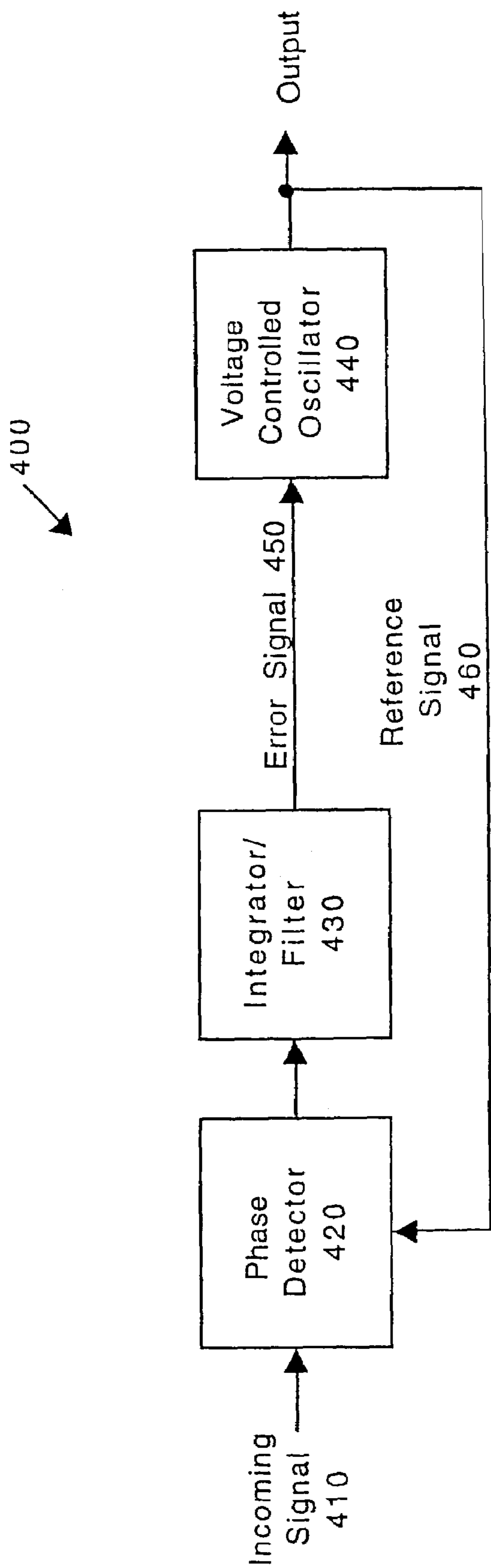


Fig. 4

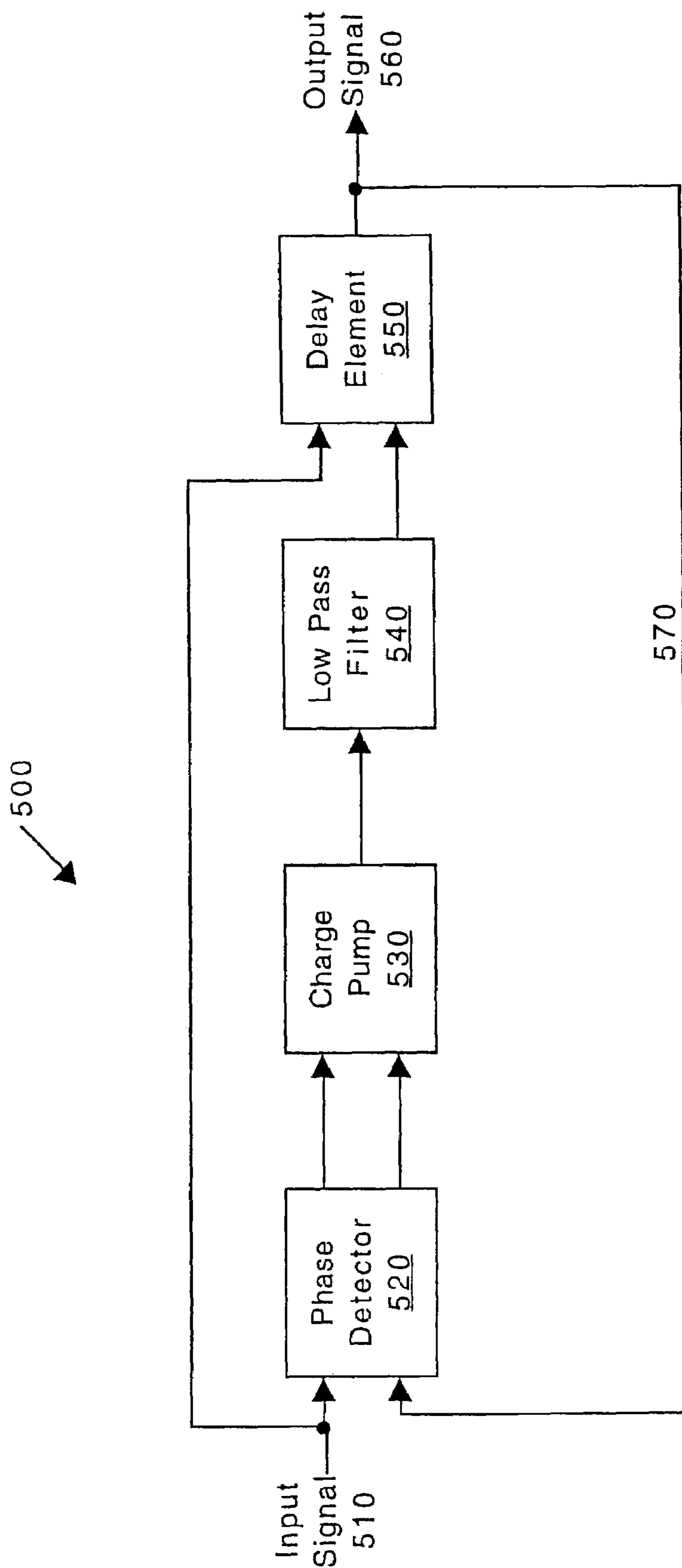


Fig. 5

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## METHOD AND APPARATUS FOR ADJUSTING THE PERFORMANCE OF A SYNCHRONOUS MEMORY SYSTEM

This application is a continuation of application Ser. No. 10/051,957, filed on Jan. 18, 2002 now U.S. Pat. No. 6,553,452, which is a continuation of application Ser. No. 08/948,774, filed on Oct. 10, 1997 (now U.S. Pat. No. 6,513,103).

The present invention relates to digital memory systems, and more specifically, to synchronous memory systems.

### BACKGROUND OF THE INVENTION

As the operational frequencies of digital computing systems continue to increase, it has become increasingly necessary to use synchronous memory systems instead of the slower asynchronous memory systems. In synchronous memory systems, data is sent between a master device and one or more memory devices in the form of data packets which travel in parallel with, and must maintain precise timing relationships with, a system clock signal.

Because synchronous memory systems impose tight timing relationships between the clock and data signals, the memory interface circuits in the memory devices of the synchronous memory system generally require clock recovery and alignment circuits such as phase locked loops (PLLs) or delay locked loops (DLLs). One drawback of these clock recovery and alignment circuits, however, is that they typically operate effectively only over a limited range of frequencies. For example, a PLL may not be able to lock to the system's clock frequency if the frequency is either too low or too high. Additionally, the performance of these clock recovery and alignment circuits is degraded due to conditions such as temperature, supply voltage, speed binning codes, process, dimensions (i.e. length) of the memory bus, etc.

### SUMMARY OF THE INVENTION

It is an object of this invention to provide for an adjustable synchronous memory control system.

It is a further object of this invention to provide for a synchronous memory control system that uses frequency information to improve the performance of the circuits at the system clock frequency.

It is a further object of this invention to provide for a synchronous memory system that uses system parameters to improve the performance of the circuits at the system clock frequency.

The present invention is a method for adjusting the performance of a synchronous memory control system. A memory system comprises a master device and a slave device. A memory channel couples the master device to the slave device such that the slave device receives the system operating information from the master device via the memory channel. The slave device further includes means for tuning circuitry within the slave device such that the performance of the memory system is improved.

Other objects, features, and advantages of the present invention will be apparent from the accompanying drawings and from the detailed description that follows below.

### BRIEF DESCRIPTION OF THE DRAWINGS

The present invention is illustrated by way of example, and not by way of limitation, in the figures of the accom-

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panying drawings and in which like reference numerals refer to similar elements and in which:

FIG. 1 illustrates one embodiment of the synchronous memory system of the present invention.

FIG. 2 illustrates a portion of the synchronous memory system of FIG. 1.

FIG. 3 illustrates one embodiment of the memory interface circuitry inside a memory device of the present invention.

FIG. 4 illustrates a block diagram of one embodiment of a phase locked loop (PLL) circuit that may be used in the present invention.

FIG. 5 illustrates a block diagram of one embodiment of a delay locked loop (DLL) circuit that may be used in the present invention.

### DETAILED DESCRIPTION

A method and apparatus for adjusting the performance of a memory system is described. The present invention is for a synchronous memory system wherein the master device has information about its operating frequency and transmits this frequency information to the memory devices. The memory devices then use this frequency information to adjust their clock recovery and alignment circuits to improve their performance at the system clock frequency. The master device may send the memory devices information that specifies the exact frequency of operation, or alternatively, the master device may send the memory devices information that specifies a predetermined range of frequencies which includes the system's clock frequency. For one embodiment, the frequency information is sent as a digital code that is received, stored, and decoded by the memory devices to produce a control code for adjusting the performance of the clock recovery and alignment circuits.

The synchronous memory system operates by sending and receiving data in packets which are synchronized with respect to a system clock. In order to do this properly, the memory master as well as all the slave devices must include circuitry that ensures that the data is read/written synchronously with the system clock. This circuitry is placed within the interface circuits of the memory master and slave devices. The key function of this circuitry is to produce internal clock signals within each device that maintain the proper phase relative to that of the external system clock such that data read or written to the channel by each of the devices is done so at the correct time, thereby preserving synchronization in the memory system. Because the memory devices may be used in different systems which use different operating clock frequencies, this circuitry should function effectively over a large range of possible system clock frequencies.

FIG. 1 illustrates one embodiment of the synchronous memory system of the present invention. This system comprises a master device **110**, a memory bus **180**, one or more memory devices **120**, **130**, a system clock source **150**, and a terminator **140**.

The master device **110** can be a memory controller, a microprocessor, a 3-D firmware chip, or any other microchip that accesses the synchronous memory. The master device **110** includes a memory interface circuit **115** for transmitting and receiving data from the memory bus **180**. The master device **110** generates requests to store data into or recover data from the memory devices **120**, **130** via the memory bus **180**.

The memory bus **180** is a data communications channel. For one embodiment, the memory bus **180** is a collection of



wires or transmission lines. For one embodiment, the memory bus 180 comprises matched-impedance printed circuit board traces.

For one embodiment, the memory devices 120, 130 are dynamic random access memories (DRAMs). Alternatively, the memory devices 120, 130 are static random access memories (SRAMs) or other memory devices, each memory device 120, 130 includes a memory interface circuit 125, 135, respectively, for transmitting and receiving data from the memory bus 180. For one embodiment, the memory devices 120, 130 cannot generate requests for data but instead only respond to requests generated by the master device 110.

The clock source 150 provides the synchronizing clock signal for the memory system at a system clock frequency. In FIG. 1, the clock source 150 is shown providing this clock signal to a signal line called CTM 160 (clock-to-master). In this implementation, the clock signal travels along the memory bus 180 from the clock source 150, past all the memory devices 120, 130, to the master device 110. At the master device 110, CTM 160 connects to another signal line called CFM 170 (clock-from-master). Thus, the clock signal travels back along the memory bus 180 in the opposite direction, away from the master device 110, past all the memory devices 120, 130 and to the terminator 140. Data sent from the master device 110 to the memory devices 120, 130 travels in parallel with the clock signal on CFM 170. Likewise, data sent from the memory devices 120, 130 to the master device 110 travels in parallel with the clock signal of CTM 160.

The terminator 140 provides a matched-impedance termination for the transmission lines of the memory bus 180. For one embodiment, all signals transmitted on the memory bus 180 eventually terminate at the terminator 140. Although it is included in the synchronous memory system of FIG. 1, some synchronous memory systems do not use a terminator 140. For one embodiment, the terminator 140 is a plurality of resistors, coupled to the memory bus 180, preventing reflection of the signal.

FIG. 2 shows a more detailed drawing of a portion of a synchronous memory system. In order to show more detail, only the master device 110, one memory device 120, and the portion of the memory bus 180 that connects these two devices is shown. FIG. 2 shows the memory interface circuits 115, 125 for both the master device 110 and the memory device 120. Furthermore, the figure shows the clock recovery and alignment circuits 210, 220 (CRA circuits) within the interface circuits 115, 125, respectively. FIG. 2 also shows the internal clock lines 215, 225 which are driven by the CRA circuits 210, 220. These internal clock lines 215, 225 serve to synchronize the receive and transmit circuitry in the memory interface circuit 115, 125 to the system clock signals.

The master device 110 further includes information circuitry 290. The information circuitry holds information about the system's clock frequency and other system-level information. For one embodiment, the information circuitry 290 holds system clock frequency information. The information circuitry 290 may detect and/or store other information which affects circuit functioning. For one embodiment, the information circuitry 290 may detect and/or store information about the system temperature, or temperature ranges. The information circuitry 290 may detect and/or store information about the supply voltage, or voltage range. The information circuitry 290 may further detect and/or store information about the length of the memory bus 180, speed binning codes, process, and other factors that may affect the

operation of the memory system. For one embodiment, the information circuitry 290 includes a PVTR detector. Detecting and storing this type of information is known in the art, as is the influence of the various factors on system operation. For one embodiment, the data in the information circuitry is also used to tune the performance of the CRAC 210 in the master device's memory interface 115.

For one embodiment, the same information about frequency, voltage, temperature, etc. that is sent to the memory devices to tune the performance of their CRACs is also made available to a CRAC inside the master device to tune its performance. Chip-specific information about the master device, such as the master device's process condition may be used along with the information that is sent to the memory devices to tune the performance master device's CRAC.

The master device 110 uses the memory bus 180 to access data and control the memory device 120. The master device 110 improves the performance of the CRACs in the memory device 120 by sending frequency information through the memory bus 180 to the memory device 120. For one embodiment, the frequency information is sent as a digital code to the memory device 120. Alternatively, for more accuracy, the frequency information may be sent as an analog signal.

FIG. 2 also shows the memory bus 180 in greater detail. The signal lines shown in FIG. 2 illustrate the types of signal lines present, in one embodiment. However, the number of signal lines illustrated do not correspond to the actual number of signal lines. The memory bus 180 includes the clock signal lines 250, CTM 160 and CFM 170, described above.

For one embodiment, the memory bus 180 includes a plurality of high-speed data lines 230, 270 which transmit data information between the master device 110 and the memory device 120 in parallel with either the CTM 160 or CFM 170 clock signals. The memory bus 180 also includes a plurality of high-speed control signal lines 240, 260 for transmitting address, request, acknowledge, and other control signals. Finally, the memory bus 180 includes lower-frequency "sideband" lines 280 for communicating information at lower speed between the master device 110 and the memory device 120.

For one embodiment, the memory channel includes slow speed lines and high speed lines. For one embodiment, the slow speed lines are used for system control such as nap, and the high speed lines are used for data and addressing. The controller is aware of its operating frequency and communicates this information to the slave devices. For one embodiment, the master device communicates this information to the slave devices via the slow speed lines. The slave devices receive, decode, and use this frequency information to adjust the circuits in their CRACs to improve their performance at the system clock frequency and other operating conditions. In other words, frequency control information comes down the slow speed lines to adjust/improve the performance of the high speed lines. For an alternative embodiment, there is only one channel that operates first at low speed to send frequency control information to adjust the CRACs and then operates at high speed after adjustment. For another alternative embodiment, there is only one channel that always operates at high speed, but until the frequency control information has been sent, it operates with lower initial margin.

For one embodiment, the master device 110 sends the memory device 120 information that specifies the exact frequency of operation. For another embodiment, the master device 110 sends the memory device 120 information that



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specifies a predetermined range of frequencies which includes the system's clock frequency.

For one embodiment, the master device further includes a PVTR detector, and the information circuit **290** further sends information from this PVTR circuit to the slave devices. In one embodiment, the master has a PVTR detector or other detector for detecting system operating parameters. The master sends this information to the slave devices so that they can adjust their performance. This data can be sent via any of the 3 ways described above, i.e. over a separate slow speed channel, over a temporarily slow speed channel, or over an initially low margin high speed channel.

In an alternative embodiment, each individual slave device has a PVTR detector to control the performance of its own CRAC circuits.

In yet another embodiment, the master sends frequency information to the slaves, but each slave also has its own PVTR detector. The frequency data is combined with the PVTR data to properly adjust the CRA circuits to account for both of these two types of operating information.

For one embodiment, such information is sent to the memory device **120** periodically during operation of the memory system. For another embodiment, the information is sent only once, during initialization of the memory system.

FIG. 3 shows a close-up view of one embodiment the memory interface circuitry **125** inside a memory device **120** of the present invention. The memory interface circuitry **125** includes a clock recovery and alignment circuit **310** (CRA circuit), transceiver circuitry **330**, an n-bit wide register circuit **340**, and an m-output decoder circuitry **350**. The transceiver circuitry **330** is designed to receive data from and/or transmit data to the memory bus **180**. The m-output decoder circuitry **350** is designed to decode the frequency information sent by the master device **110** and stored in the register circuit **340** to produce a corresponding m-bit control code.

The master device **110** (not shown) sends the information about the system's operating frequency to the memory device **120**. The frequency information is encoded onto n bits as described below. This frequency information is then received by the transceiver circuitry **330** in each memory device **120**. The use of transceiver circuitry **330** for receiving data from the memory bus **180** is well-known in the art. Upon receiving this information about the system's clock frequency, the transceiver circuitry **330** stores it into the n-bit register circuit **340**. For one embodiment, the frequency information is stored in the register circuit **340** during normal system operation or at the initialization of the system.

The n-bit register circuit **340** presents this frequency information to a decoder circuitry **350**. The decoder circuitry **350** translates this frequency information into a m-bit control code for adjusting the performance of the CRA circuitry **310**. For one embodiment, the control code is used to adjust one or more portions of the CRA circuitry **310** such that the circuitry operates effectively at the system's clock frequency. For another embodiment, the control code adjusts the CRA circuitry **310** to optimize for external factors, such as temperature, memory bus **180** length, supply voltage, etc.

There are several ways that the frequency information can be encoded into n bits and then sent to and stored in the memory device **120**. For one embodiment, a binary word indicates the time period of the system clock in pico-seconds (ps), where period=1/frequency. For example, using a 16-bit register, a 16-bit digital word can be sent to the memory device **120** that indicates with 1 ps precision that the system's clock period is anywhere from 0 ps to 65,535 ps

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( $2^{16}-1$ ). Alternatively, a more compact digital code that indicates one of a predetermined range of frequencies which includes the system's clock frequency may be used. This scheme requires the storage of fewer bits than the first scheme, but only specifies a range of frequencies instead of an exact frequency. One example of a compact code that could be used, and its corresponding range of frequencies, is shown in the table below:

TABLE 1

Code Indicating Frequency Range				
Compact Code Bits		Minimum Frequency	Maximum Frequency	Frequency Range Size
C1	C0	(fmin)	(fmax)	(Delta_F)
0	0	238 MHz	282 MHz	44 MHz
0	1	278 MHz	327 MHz	49 MHz
1	0	323 MHz	382 MHz	59 MHz
1	1	378 MHz	447 MHz	69 MHz

As can be seen, this scheme uses only 2 bits instead of 16 bits.

Once the frequency information has been stored in the n-bit register circuit **340**, the decoder circuitry **350** evaluates this n-bit data to produce the required m-bit control code for adjusting the CRA circuitry **310** for optimal operation. For one embodiment, the control code that is decoded from the frequency information specifies a range of operating frequencies. This is simple if the register circuit **340** is given a compact code that specifies a range of frequencies which includes the system's clock frequency. The decoder circuitry **350** is more complex if the register circuit **340** holds the period of the system's clock signal. For one embodiment, the decoder circuitry **350** includes a simple look-up table for frequency ranges corresponding to control codes. For one embodiment, these tables are hard wired. For one embodiment, these tables may be altered by a user. The decoded control code is then sent to the CRA circuit **310**.

The CRA circuit **310** adjusts the phase of internal clock signals so that the receive and transmit circuitry of the memory device **120** will be synchronized with the system clock signals CTM & CFM. The CRA circuit **310** may include variable delay elements, phase interpolator (mixer) circuits, and slew rate control circuits. By receiving and responding to these control codes, these circuits enable the synchronous memory system to operate effectively over a larger range of system clock frequencies than would be possible without the control codes. For one embodiment, the CRA circuit **310** is a phase locked loop (PLL) circuit. For another embodiment, the CRA circuit **310** is a delay-locked loop (DLL) circuit.

The control codes are used to adjust the locking frequency range of the clock recovery and alignment circuits to include the operating clock frequency of the system. The control codes are also used to reduce the jitter of the signals on the high-speed lines, and to improve the timing margin of the signals on the high-speed lines.

FIG. 4 illustrates a block diagram of one embodiment of a phase locked loop (PLL) circuit. The phase locked loop **400** is a feed back device that attempts to lock to the phase of an incoming signal. The phase detector compares the phase of the incoming signal **410** to that of the reference signal **460**. The reference signal **460** is the output of the PLL **400**, and it also serves as the feedback signal for the PLL system.



An input signal **410** is an input to the phase detector **420**. For one embodiment, the input signal **410** is a system clock signal such as CTM. The output of phase detector **420** is an input to integrator/filter **430**. The output of integrator/filter **430** is input to a voltage controlled oscillator (VCO) **440**. The output of the VCO **440** is the output of the phase locked loop **400**. The output of the VCO **440** is the reference signal **460**, which is input to the phase detector **420**.

An example of how the phase locked loop works is as follows. At the beginning the loop is in balance, i.e. the loop error is equal to zero. Assume that the frequency of the incoming signal increases slightly. This means that the phase of that signal changes a little faster—phase is the integral of frequency. Accordingly, the loop error becomes positive because the phase of the reference signal cannot change at once due to inherent delays in the PLL **400**. The frequency generated by the VCO **440** follows the changes in the error signal so that it also increases. The final consequence is that an increase in the incoming signal's frequency causes an increase in the frequency of the reference signal. Thus, the reference signal **410** and incoming signal **410** converge on the same frequency. The elements of the PLL **440** are known in the art.

FIG. **5** illustrates a block diagram of one embodiment of a delay locked loop (DLL) circuit that can be used in the CRAC. An input signal is placed on input line **510** of the delay locked loop **500**. The input signal is also an input to the delay element **550**. The phase detector **520** functions to compare the phase difference between the input signal **510**, and a feedback signal on feedback loop **570**, and to generate two possible outputs, up, and down, representing the phase difference between the input signal and the feedback signal. The up and down signal outputs of the phase detector **520** are input to a charge pump **530**. The charge pump is controlled by the up and down signals to raise or lower the voltage on its output line. The voltage on the output line is an input to a low pass filter **540**, where it is filtered and delivered to delay element **550**. The delay element **550** functions to delay the input signal, in proportion to the voltage delivered by the low pass filter **540**. This delayed signal is the output signal on line **560**, and is fed back to the phase detector **520** via the feedback line **570**.

Although this disclosure has stressed the use of frequency information to tune the clock recovery and alignment circuit of the memory device **120**, other relevant information could be transmitted to the memory device **120** and held by its register circuit **340** to tune the performance of clock recovery and alignment circuits. Examples of other types of information that could be sent from the master to the memory device **120** are temperature, supply voltage, speed binning codes, dimensions of the memory bus **180**, etc. Any one or more of these types of information could be sent from the master device **110** to the memory device **120** to tune the memory device **120** circuits to operate more effectively under the system's operating conditions.

What is claimed is:

**1.** A dynamic random access memory device having an array of dynamic memory cells, wherein the memory device comprises:

- a receiver to sample an externally provided value that is representative of a supply voltage being provided to the memory device;
- a programmable register, coupled to the receiver, to store the value; and

a register to store data transfer rate information, wherein an internal circuit is adjusted based on the data transfer rate information and the value stored in the programmable register.

**2.** A dynamic random access memory device having an array of dynamic memory cells, wherein the memory device comprises:

- a receiver to sample an externally provided value that is representative of a supply voltage being provided to the memory device; and
- a programmable register, coupled to the receiver, to store the value; and
- a clock synchronization circuit to receive an external clock signal and synchronize outputting of data from the memory device with the external clock signal.

**3.** The memory device of claim **2** wherein the clock synchronization circuit includes one of a delay locked loop circuit and a phase locked loop circuit.

**4.** The memory device of claim **2** wherein the clock synchronization circuit includes:

- a phase detector to generate information representative of a difference in phase between the external clock signal and the internal clock signal; and
- a delay circuit to generate the internal clock signal, wherein an amount of delay of the internal clock signal is varied based on the information representative of the difference in phase between the external clock signal and the internal clock signal.

**5.** The memory device of claim **2** wherein the programmable register is coupled to the clock synchronization circuit and wherein the clock synchronization circuit is adjusted in accordance with the value stored in the programmable register.

**6.** A dynamic random access memory device having an array of dynamic memory cells, wherein the memory device comprises:

- receiver means for sampling an externally provided value that is representative of a supply voltage being provided to the memory device;
- a programmable means, coupled to the receiver means, for storing the value; and
- means for storing data transfer rate information, wherein an internal circuit is adjusted based on the data transfer rate information and the value stored in the programmable means.

**7.** A dynamic random access memory device having an array of dynamic memory cells, wherein the memory device comprises:

- receiver means for sampling an externally provided value that is representative of a supply voltage being provided to the memory device;
- a programmable means, coupled to the receiver means, for storing the value; and
- clock synchronization means to receive an external clock signal and synchronize outputting of data from the memory device with the external clock signal, wherein the clock synchronization means is adjusted based on the value stored in the programmable means.

**8.** The memory device of claim **7** wherein the clock synchronization means includes:

- a phase detector to generate information representative of a difference in phase between the external clock signal and an internal clock signal; and
- a delay circuit to generate the internal clock signal, wherein an amount of delay of the internal clock signal is varied based on the information representative of the



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difference in phase between the external clock signal and the internal clock signal.

9. A method of controlling a dynamic random access memory device by a memory controller, wherein the method comprises:

in the memory controller, accessing information indicative of a supply voltage potential; and

providing the information to the memory device, the memory device to process the information such that a clock alignment circuitry in the memory device is adjusted based on the supply voltage potential.

10. The method of claim 9 wherein the information is provided to the memory device during initialization of the memory device.

11. The method of claim 9 further including providing information indicative of a data transfer rate to the memory device.

12. The method of claim 9 further including providing information indicative of a range of data transfer rates to the memory device.

13. The method of claim 9 wherein accessing the information includes detecting the supply voltage.

14. A method of operation in a memory device that includes a plurality of memory cells, the method comprising:

receiving a value which is representative of a supply voltage potential being provided to the memory device; and

adjusting a clock alignment circuit based on the value, the clock alignment circuit to synchronize transmission of data from the memory device.

15. The method of claim 14 wherein the value is issued to the memory device during an initialization period.

16. The method of claim 14 wherein the clock alignment circuit synchronizes transmission of data such that the data is transmitted synchronously with respect to a clock signal.

17. The method of claim 14 further including decoding the value to generate an internal control signal, wherein the clock alignment circuit is adjusted in response to the internal control signal.

18. The method of claim 14 wherein adjusting the clock alignment circuit includes adjusting a phase mixer in accordance with the value.

19. The method of claim 14 wherein the clock alignment circuit is a delay lock loop circuit, wherein the delay lock loop circuit generates an internal clock signal having a predetermined timing relationship with an external clock signal to synchronize the transmission of the data from the memory device.

20. The method of 14 wherein the clock alignment circuit is a phase lock loop circuit, wherein the phase lock loop circuit generates an internal clock signal having a predetermined timing relationship with an external clock signal to synchronize the transmission of the data from the memory device.

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21. The method of claim 14 further including adjusting a locking frequency range of the clock alignment circuit, wherein the locking frequency range is adjusted based on the value.

22. The method of claim 14 further including generating an internal clock signal using the clock alignment circuit, the internal clock signal having a predetermined phase relationship with an external clock signal, wherein the internal clock signal synchronizes the transmission of the data from the memory device.

23. The method of claim 22 further including: detecting a phase differential between the external clock signal and the internal clock signal; generating the internal clock signal using a delay element; and

varying an amount of delay in the delay element to adjust the phase differential between the internal clock signal and the external clock signal.

24. The method of claim 14 further including: receiving information which is representative of a data transfer rate; and storing the information which is representative of a data transfer rate in a register disposed within the memory device.

25. A synchronous integrated circuit memory device having an array of dynamic memory cells, wherein the memory device comprises:

a plurality of receivers to receive an externally provided value that is representative of a supply voltage potential; and

a locked loop circuit, coupled to a plurality of transmitters, to synchronize transmission of data from the memory device with an external clock signal, wherein the locked loop circuit is adjusted using the value.

26. The integrated circuit memory device of claim 25 wherein the locked loop circuit further includes a mixer circuit to vary a phase range of an internal clock signal in accordance with the value, wherein the locked loop circuit synchronizes the transmission of data from the memory device with the external clock signal using the internal clock signal.

27. The integrated circuit memory device of claim 25 further including:

a programmable register to store the value; and decoder circuitry coupled to the programmable register to decode the value stored within the programmable register.

28. The integrated circuit memory device of claim 27 further including a register to store data transfer rate information, wherein the locked loop circuit is adjusted in accordance with the value stored in the programmable register and the data transfer rate information.

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